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Vitamin D Supplementation Enhances the Fixation of Titanium Implants in Chronic Kidney Disease Mice

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Abstract

Vitamin D (Vit D) deficiency is a common condition in chronic kidney disease (CKD) patients that negatively affects bone regeneration and fracture healing. Previous study has shown that timely healing of titanium implants is impaired in CKD. This study aimed to investigate the effect of Vit D supplementation on implant osseointegration in CKD mice. Uremia was induced by 5/6 nephrectomy in C57BL mice. Eight weeks after the second renal surgery, animals were given 1,25(OH)₂D₃ three times a week intraperitoneally for four weeks. Experimental titanium implants were inserted into the distal end of femurs two weeks later. Serum measurements confirmed decreased 1,25(OH)₂D levels in CKD mice, which could be successfully corrected by Vit D injections. Moreover, the hyperparathyroidism observed in CKD mice was also corrected. X-ray examination and histological sections showed successful osseointegration in these mice. Histomorphometrical analysis revealed that the bone-implant contact (BIC) ratio and bone volume (BV/TV) around the implant were significantly increased in the Vit D-supplementation group. In addition, resistance of the implant, as measured by a push-in method, was significantly improved compared to that in the vehicle group. These results demonstrate that Vit D supplementation is an effective approach to improve the fixation of titanium implants in CKD.

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Introduction

Chronic kidney disease (CKD) is recognized as a global public health threat. It is a highly prevalent disease with severe complications, such as cardiovascular disease and chronic kidney disease-mineral and bone disorders (CKD-MBD) [1–3]. Screening conducted by nephrologists from all over the world indicates that the incidence of CKD is increasing with ranges of 10.2% to 20% of the population [4–7]. According to a recent cross-sectional survey in China, the prevalence of CKD adults was 10.8%, which means that approximately 119.5 million people are affected by CKD in this rapidly developing country [8].

Declining renal function negatively affects the status of oral health. A recent systematic review showed that poor oral health is a common and often severe side-effect for adults with CKD [9]. Approximately 90% of CKD patients suffer from oral symptoms, including both hard and soft tissues [10–14]. Studies have demonstrated that CKD profoundly influences bone remodeling [15] and the structure of the mandible [16]. Furthermore, cross-sectional radiographic examinations indicate that CKD patients experience much more severe alveolar bone loss [17].

Although dental implants have been widely used in clinical settings, opinions regarding implants for CKD patients vary. Both the oral and nephrological literature suggests that dental implant surgery may be contraindicated in patients with significant renal

osteodystrophy [18,19]. However, other investigations into the quantity and quality of the alveolar bone of dialysis patients showed that the residual bone volumes were adequate for implant insertion, suggesting this type of treatment is applicable to CKD patients [20]. Previously, we studied the effect of CKD on osseointegration of titanium implants using a uremic mouse model. Although all implants were able to be successfully integrated, CKD significantly decreased the bone-implant strength at an early stage in healing [21]. Therefore, enhancement of dental implant osseointegration in CKD patients remains a challenge.

Vitamin D deficiency is common in CKD patients [22–26] and this deficiency may negatively affect bone regeneration and fracture healing due to its importance in bone metabolism [27]. Low serum 1,25-dihydroxyvitamin D triggers higher levels of serum PTH [28,29], which in turn promotes high bone turnover, exacerbates osteopenia and finally results in cortical bone loss and pathogenesis of osteoporosis [30–32]. Kelly *et al.* [15] showed that vitamin D insufficiency impairs the osseointegration of Ti6Al4V implants in male Sprague-Dawley rats. Alvim-Pereira *et al.* [33] observed no association between a vitamin D receptor polymorphism (rs731236, TaqI) and dental implant loss. On the other hand, vitamin D supplementation has demonstrated a significant survival advantage in CKD patients [25], and accelerated cellular

events in the process of fracture healing [34]. These findings suggest a potentially beneficial role for vitamin D in promoting implant osseointegration in CKD patients. In this study, we established a CKD mouse model to investigate the effect of vitamin D supplementation on fixation of titanium implants. The results are expected to be a significant contribution to dental implant therapy in CKD patients.

Materials and Methods

Ethics Statement

This study was carried out in strict accordance with the recommendations contained in the Guide for the Care and Use of Laboratory Animals of the National Institutes of Health and the ARRIVE guidelines (<http://www.nc3rs.org/ARRIVE>). All of the experiments performed were approved by the Subcommittee on Research and Animal Care (SRAC), which serves as the Institutional Animal Care and Use Committee (IACUC) at the Harvard Medical School (protocol number: 03901). All surgery was performed under anesthesia by intraperitoneal injection of a combination of ketamine (100 mg/ml) and xylazine (10 mg/ml), in addition, buprenorphine (0.05 mg/kg) was given for perioperative analgesia to minimize suffering and pain.

Animals

Thirty 9-week-old female C57BL mice (body weight: 22.0±2.0 g) were obtained from Charles River Laboratories International Inc. (Wilmington, MA) and randomly assigned to three groups: control (n = 10), CKD (n = 10), and CKD+Vit D (n = 10). The animals were kept under climate-controlled conditions (25°C; 55% humidity; 12 hours of light alternating with 12 hours of darkness) and fed with a standard diet.

Surgical Procedure to Induce Uremia

CKD is induced in mice by a two-step 5/6 nephrectomy to produce uremia as described previously [21]. Briefly, the first procedure involves electrocautery of the left kidney except for a 2-mm area around the hilum. After 1 week, a total nephrectomy of the right kidney is performed by ligation of the renal hilum and surgical excision. Sham surgery consists of anesthetic administration, flank incision exposing the kidney, and closure of the abdominal wall.

Supplement of Active Vitamin D

The active form of vitamin D [$1,25(\text{OH})_2\text{D}_3$], was obtained from Enzo Life Sciences Inc. (Farmingdale, NY) and diluted in saline. Eight weeks after the second kidney surgery, mice in the Vit D-treated group were injected with Vit D (100 ng/kg body weight) 3 times a week until they were sacrificed. Saline was used as a vehicle. The workflow is shown in Fig. S1.

Implant Surgery

Ten weeks after the second surgery (renal ablation), the mice were subjected to implant placement using the method described by Xu *et al.* [35]. Titanium implants with SLA surface (1 mm in diameter and 4 mm in length) were obtained from Institut Straumann AG (Basel, Switzerland). They were cut to the length of 2 mm before insertion. After careful exposure of the distal aspects of the femurs via skin incision and muscle dissection, implant sites were prepared on both sides of the anterior-distal surfaces of the femurs by sequential drilling under cooled sterile saline irrigation with 0.7- and 1.0-mm surgical stainless steel twist drills. Then, the implants were press-fitted into the holes to reach primary stability. After the insertion of the implant, the muscles

were carefully sutured with 6-0 silk, which covered the implant and further guaranteed its protection in the biological environment. Then the skin was closed with 5-0 silk.

Serum Biochemical Assays

Two weeks after the insertion of titanium implants, the mice were euthanized by carbon dioxide inhalation. Prior to euthanasia, blood was collected by cheek pouch puncture. Serum biochemistry was performed using commercially available kits: blood urea nitrogen (BUN) (Roche Diagnostics, Indianapolis, IN); $1,25(\text{OH})_2\text{D}$ (Immunodiagnostic Systems Ltd., Fountain Hills, AZ); Calcium and Phosphate (Stanbio Laboratory, Boerne, TX). For the assay of serum ALP activity, the serum was diluted 25 times and measured using a SensoLyte pNPP Alkaline Phosphatase Assay Kit (AnaSpec Inc., Fremont, CA).

X-ray Examination and Histological Preparation

Two weeks after implant placement, one femur carrying an implant was harvested from each mouse and fixed in 10% buffered formalin for 1 week at 4°C. Specimens were exposed to X-ray (20 kV, 5 seconds), and then dehydrated and embedded in light-curing epoxy resin (TechnoVit 7200VLC, Hereaus Kulzer, Wehrheim, Germany). Embedded specimens were cut perpendicular to the longitudinal axis of the implants at a site 0.5 mm from its apical end. The specimens were then ground to a thickness of about 50 μm with a grinding system (Exakt Apparatebau, Norderstedt, Germany). Sections were stained with Stevenel's blue and Van Gieson's picro fuchsin stain, and observed by light microscopy.

Histomorphometric Measurement

Images of the implant and peri-implant bone tissues were digitized and histomorphometrically analyzed with NIH Image J (National Institutes of Health, USA). Bone-implant contact (BIC) was calculated as the linear percentage of direct bone-to-implant contact to the total surface of the implant. And the bone volume (BV/TV) in the circumferential zone within 100 μm of the implant surface was calculated. The following formulas were used for analysis.

$$\text{Bone – implant contact (\%)} = \frac{(\text{sum of the length of bone / implant contact})}{(\text{circumference of the implant})} \times 100\%$$

$$\text{Bone volume} = \frac{(\text{bone area in } 100\mu\text{m zone})}{(\text{area of } 100\mu\text{m zone})} \times 100\%.$$

Implant Biomechanical Push-in Test

The remaining femur from each mouse was harvested and embedded into auto-polymerizing resin with the top surface of the implant level. A test machine (AG-TA electronic universal testing machine, SHIMADZU, Japan) equipped with a pushing rod (diameter = 0.8 mm) was used to load the implant vertically downward at a crosshead speed of 1 mm/min. The push-in value was determined by measuring the peak of the load-displacement curve.

Statistical Analysis

All values were presented as mean \pm SD. Statistically significant differences were assessed by ANOVA followed by Tukey's test for multiple comparison, or by independent student *t* test for comparison between two groups. A *p* value of less than 0.05 was considered to be statistically significant.

Results

Animals

As anticipated, all mice tolerated the surgical procedures well and survived the full experimental period. No inflammation or infection at the implant site was observed.

Serum Biochemistry

A significant increase in serum BUN was observed in the CKD (53.87 ± 6.32) and CKD+Vit D (58.45 ± 4.33) groups as compared to that of controls (20.12 ± 3.46) ($p < 0.05$), indicating the successful establishment of the uremic mouse model (Figure S2A). Vit D injections did not cause a significant change in the serum BUN level. As shown in Figure S2B, Vit D was significantly decreased in the CKD group (27.51 ± 8.35) ($p < 0.05$), while supplementing with Vit D (62.44 ± 26.88) restored it to levels comparable to those in control mice (52.35 ± 16.33). Serum PTH in the CKD group was 3.6-fold that observed in the control group ($p < 0.05$). It decreased to the levels comparable to the control upon Vit D treatment (Figure S2C). There was no significant difference in serum calcium (Figure S2D) and phosphate (Figure S2E) levels among the three groups. Serum ALP decreased significantly in the Vit D-treated group as compared to the CKD group ($p < 0.05$), although it was still significantly higher than that of control (Figure S2F).

X-ray Examination

The *ex vivo* X-ray examination of the femurs showed that the implants were surrounded with bone without any notable radiotranslucent gap, indicating successful osseointegration in all groups (Figure S3).

Histology and Histomorphometry

Examination of histological sections confirmed a direct bone-implant contact in all groups (Figure S4A). Consistent with our previous report [21], the CKD group showed a decrease of bone-implant contact ratio (BIC) when compared to that of control. The contact ratio was successfully restored to the normal level after Vit D treatment. As shown in Figure S4B, the BIC of CKD+VitD group was 75.23 ± 9.92 , over 20% higher than that of CKD mice (61.86 ± 10.11) ($p < 0.05$). We then calculated the bone volume (BV/TV) in the circumferential zone within 100 μ m of the implant surface and were able to observe a 35% increase after Vit D treatment (Figure S4C).

The Resistance of Implant

In the early healing stage (week 2), the resistance of the implant was significantly higher for the Vit D treated group (15.21 ± 4.11) compared to that of the untreated CKD mice (9.86 ± 1.89), indicating an improved strength of bone-implant integration (Figure S5). No significant difference in integration was observed between the control and CKD+VitD groups.

Discussion

Vitamin D is a pleiotropic hormone that plays a critical role in regulating mineral ion metabolism [28]. It is initially biologically inactive and requires sequential hydroxylations in the liver and

kidney to produce its active form, 1,25-dihydroxyvitamin D [28]. Vit D insufficiency is a common medical condition in CKD patients [24], where declining renal function impairs the activity of 1- α hydroxylase (1 α -OHase) in kidney, which in turn reduces its ability to convert 25(OH)₂D to its activated form, 1,25(OH)₂D. In this study, we established a uremic mouse model with significantly reduced levels of 1,25(OH)₂D using the 5/6 nephrectomy method. These data are consistent with previous studies and similar to the clinical situation in CKD patients [36,37].

Vitamin D deficiency negatively affects bone regeneration, including fracture healing, due to its importance in bone metabolism [27]. Moreover, Kelly *et al.* [15] showed that vitamin D insufficiency decreased the bone-implant contact ratio and the resistance in push-in tests. Recently, Choukroun *et al.* [38] found that Vit D deficiency slows down the process of osseointegration, and also promotes infection in the graft. A genome-wide screening also suggested that Vit D deficiency affects the osseointegration of implants by regulating the circadian rhythm system and the cartilage extracellular matrix [39].

On the other hand, vitamin D supplementation has demonstrated a significant survival advantage in CKD patients [25], including accelerated cellular events in the process of fracture healing [34]. Vitamin D supplementation has been recommended as the primary therapy by the National Kidney Foundation to control secondary hyperparathyroidism and prevent skeletal complications in end stage renal failure patients [40,41]. Two recent studies demonstrated that Vit D supplementation was able to enhance implant fixation in diabetic mellitus rats with Vit D insufficiency [42,43]. Similar results were reported in studies using normal [44] or ovariectomized animals [45,46]. In this study, we successfully corrected the decreased 1,25(OH)₂D levels in CKD mice by Vit D injection, and found that both the bone-implant contact (BIC) ratio and the resistance of implant were significantly increased after a 2-week healing period, indicating that Vit D supplementation is an effective approach to improve fixation of titanium implants in CKD.

We also found that Vit D supplementation successfully corrected the increased levels of PTH, a key hormone for bone remodeling. In CKD patients, low serum 1,25-dihydroxyvitamin D triggers higher secretion of PTH [28,29], which precipitates high bone turnover and exacerbates osteopenia and finally results in bone loss [30–32]. A meta-analysis performed by Kandula *et al.* [47] showed that any form of vitamin D (including calcitriol or a vitamin D analog) lowers PTH levels in CKD patients. In this context, we hypothesize that in addition to the direct impact of Vit D on bone healing, the normalization of PTH levels might also contribute to the enhancement of implant fixation. However the direct effect of PTH on osseointegration in CKD needs to be studied further.

It should be noted that this study was performed using a mouse model with the implants placed in the distal end of femurs. Although the rodent model has been widely used for research in implant dentistry [42,45,46], the development and characterization of the femur is different from the jaw bone. A canine or mini pig model might be a better alternative as the implants can be inserted in the jaw bone instead of the femur. However, the establishment of CKD in these large animals is not yet well-established. Clinical trials are expected to confirm whether supplement of Vit D could be a good candidate for clinical approaches to enhance the fixation of titanium implants in CKD patients.

Conclusion

In this study, we found that Vit D supplementation successfully restored serum 1,25(OH)₂D levels and corrected the hyperparathyroidism in CKD mice. The bone-implant contact ratio, bone volume around implant and the resistance of the implant were improved at 2 weeks after implantation, indicating that Vit D supplementation is an effective approach to improve the fixation of titanium implants in CKD.

Supporting Information

Figure S1 Illustration of the workflow. 1st renal surgery: electrocautery of the left kidney; 2nd renal surgery: a total nephrectomy of the right kidney; Vitamin D injections started at 9th week (100 ng/kg body weight, 3 times a week for 4 weeks). (TIF)

Figure S2 Serum biochemical measurements. (A) Serum BUN; (B) Serum Vitamin D; (C) Serum PTH; (D) Serum calcium; (E) Serum phosphate, and (F) Serum ALP activity. *: $p < 0.05$ vs Control; #: $p < 0.05$ vs CKD. (TIF)

Figure S3 X-ray examination of the femurs after 2-weeks healing. The implants were surrounded with bone without any notable radiotranslucent gap. (TIF)

Figure S4 Histological and histomorphometrical analysis of the implants after 2-week healing. (A) Representative images of undecalcified sections from all three groups; VitD injection significantly increased (B) Bone-implant contact ratio (BIC, %), and (C) bone volume (BV/TV) in the circumferential zone within 100 μ m of the implant surface. *: $p < 0.05$ vs Control; #: $p < 0.05$ vs CKD. (TIF)

Figure S5 Resistance of push-in tests 2 weeks after implant placement. Vit D supplementation corrected the resistance of implant in CKD. *: $p < 0.05$ vs control; #: $p < 0.05$ vs CKD. (TIF)

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Author Contributions

Conceived and designed the experiments: QY BL MD. Performed the experiments: WL SZ DZ HZ NS. Analyzed the data: WL XL QY. Contributed reagents/materials/analysis tools: MD BL. Wrote the paper: WL BL QY.

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